Magnetic Field Sensing with 4H SiC Diodes: Nitrogen vs Phosphorous Implantation

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This Work

- Overview of the initial stages of development for a new 4H-SiC solid-state based magnetometer intended for vectorized planetary magnetic field sensing.
  - Leverage a MOSFET as the magnetic field sensing device
  - Demonstrated sensitivity of $400\ nT/\sqrt{Hz}$ with

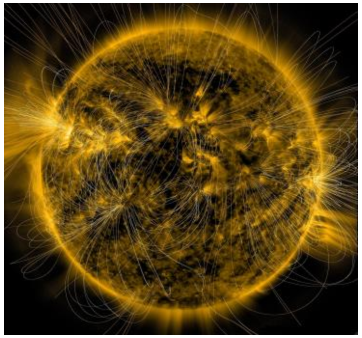
- This study will investigate the magnetic field sensing capability of two nearly identical devices
  - 4H-SiC $n^{+}p$ diodes fabricated by NASA Glenn Research Center
  - Differ only in implantation species (Nitrogen vs Phosphorous) and annealing time
  - These devices were NOT designed for magnetometry!

- Will also investigate the effect of high energy electron radiation
  - Observed a negative built-in-voltage shift in both diodes
  - No effect on maximum sensitivity!

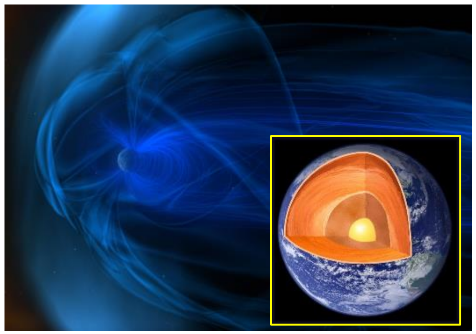
NASA’s Interest in Magnetometers

Magnetic fields in space

Heliophysics

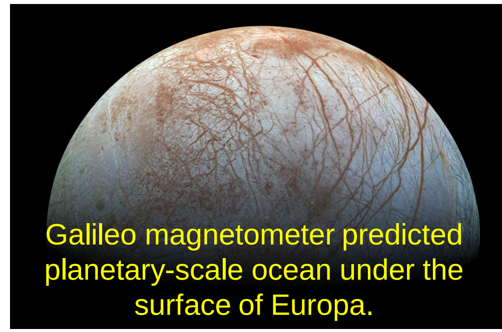


Earth & Planetary Science

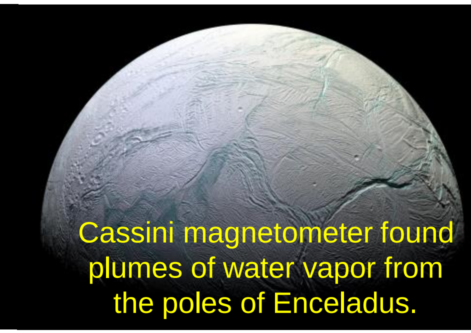


Magnetometers aid in the search for life

Europa/Jupiter



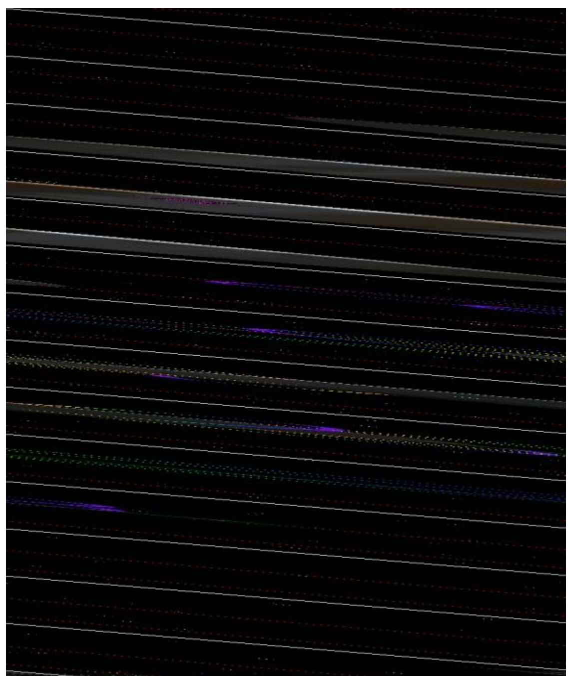
Enceladus/Saturn



Improved Magnetic Field Models

Europa / Jupiter

Simulation:
JPL’s Jupiter Environment Tool (JET) plugin for STK
Corey Cochrane, Erick Sturm



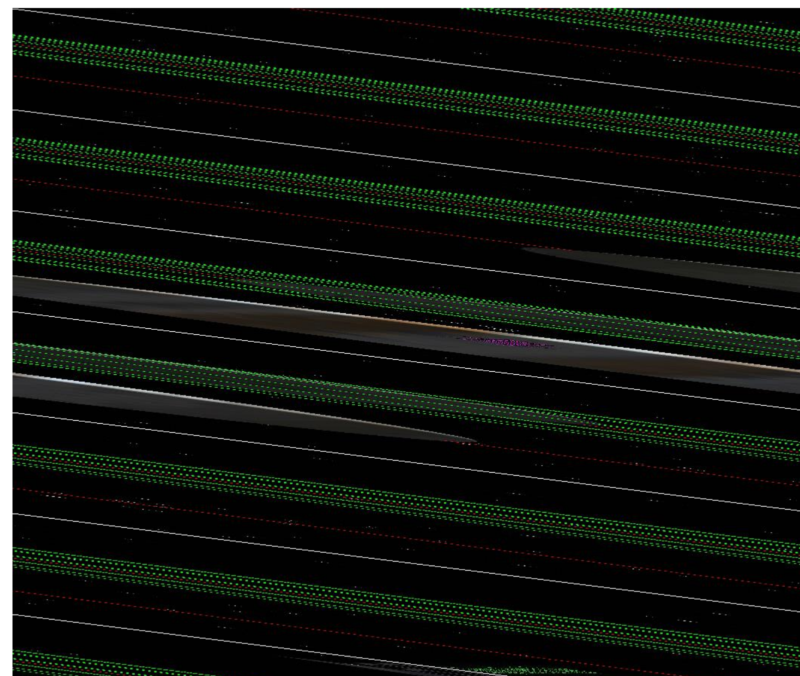


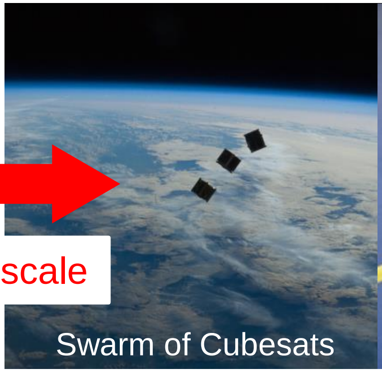
Image credit: NASA

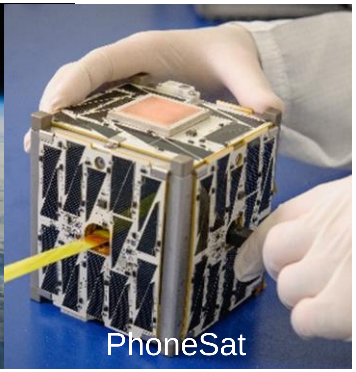
Motivation for New Technology

1. Miniaturization & lower cost

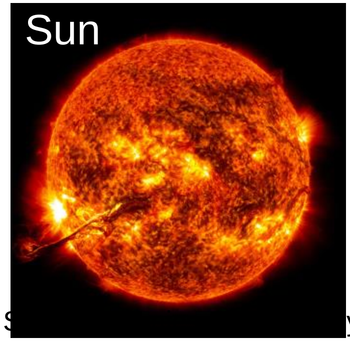
MAVEN | Pioneer 10/11

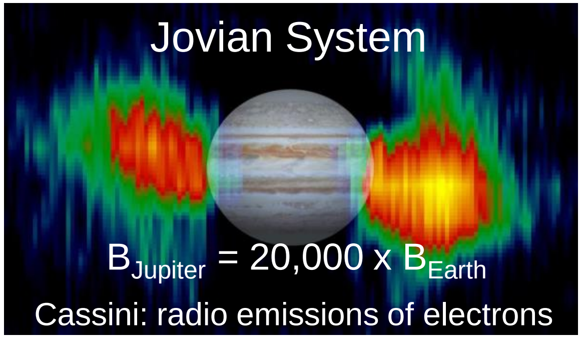

fluxgate | optically pumped

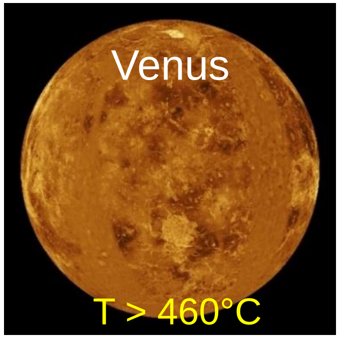




2. Extreme Environments

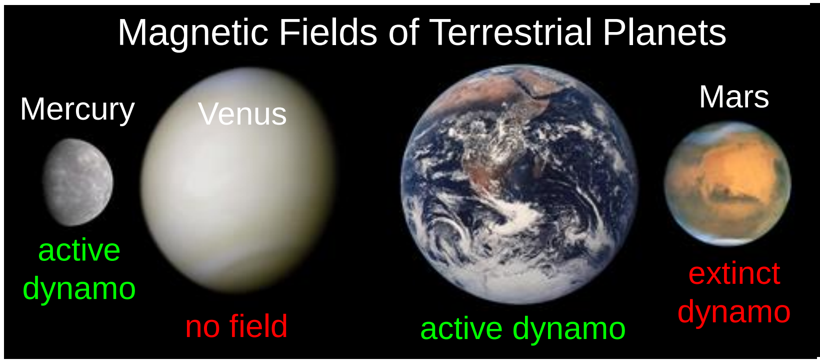


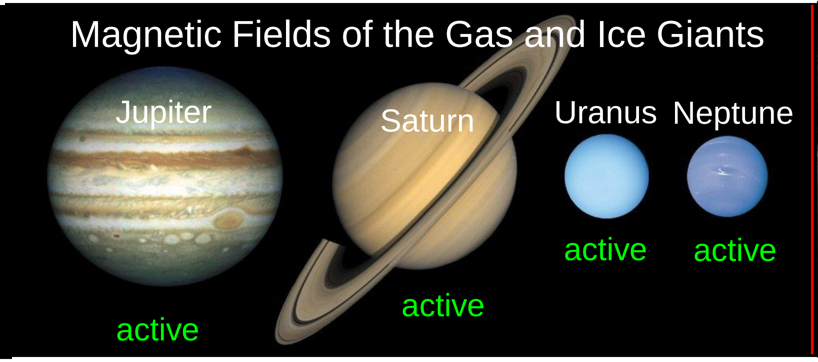


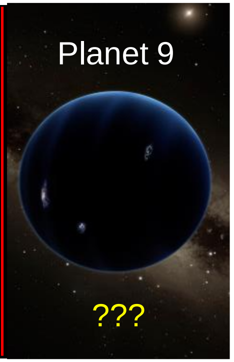


3. Still much science to be obtained!

http://nssdc.gsfc.nasa.gov/planetary/factsheet/

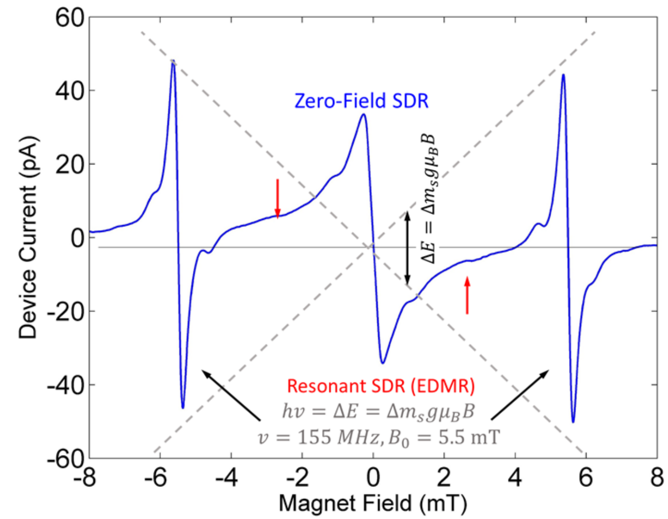




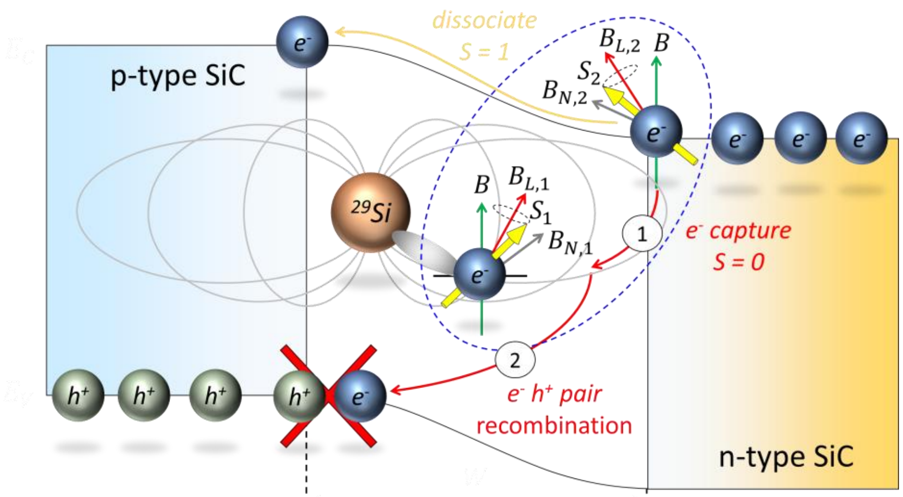


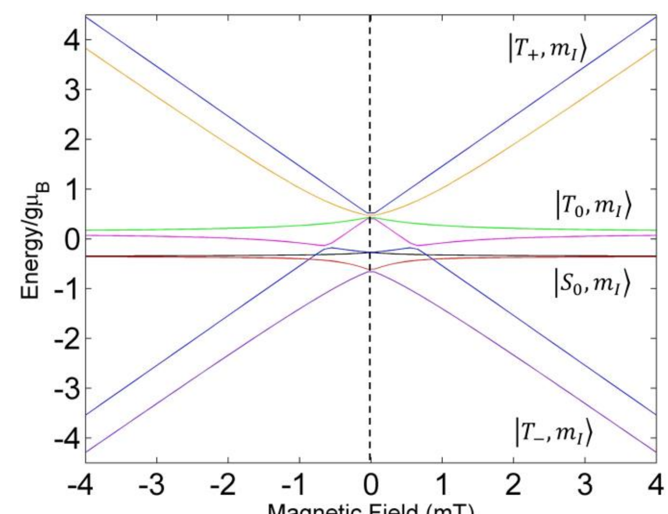
SiC Magnetometer (SiCMag)

- Sensor:
  - Simple n⁺p 4H-SiC diode
  - Spin dependent recombination (SDR) due to deep level defects
  - Leverage the zero-field detection of SDR (hyperfine mixing)
  - Robust: high temperature and high radiation environments
- Instrument:
  - Field nulling design
  - Inexpensive, simple, small footprint, low power
  - No high frequency RF or optical components
  - No dead zones
  - Simultaneous measurement of 3 axes using a single sensor
  - Potential to self-calibrate



$$\mathcal{H} = g_e \mu_B \boldsymbol{B} \cdot (\boldsymbol{S}_1 + \boldsymbol{S}_2) + \sum_i^2 \sum_j^N \boldsymbol{S}_i \cdot \boldsymbol{A}_{i,j} \cdot \boldsymbol{I}_j + \boldsymbol{S}_1 \cdot \boldsymbol{J} \cdot \boldsymbol{S}_2 + \boldsymbol{S}_1 \cdot \boldsymbol{D} \cdot \boldsymbol{S}_2$$



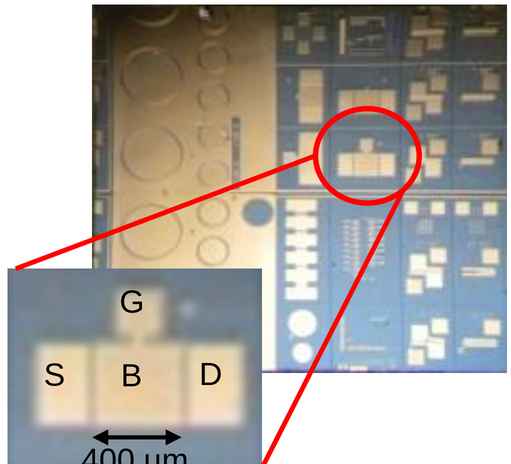


Magnetometer Instrument

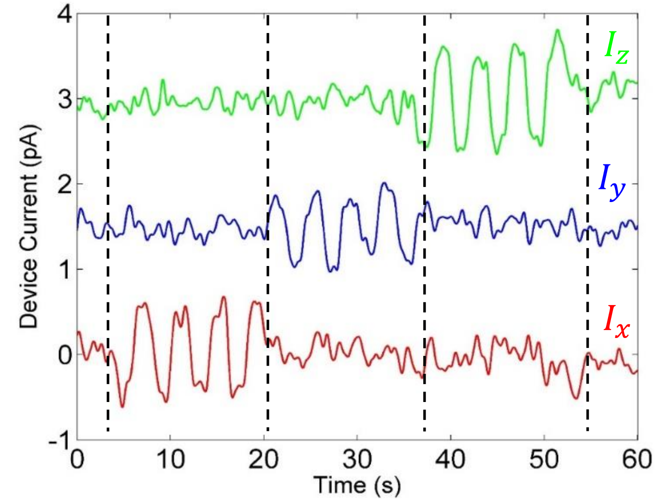
Cochrane, C. J. et al. Vectorized magnetometer for space applications using electrical readout of atomic scale defects in silicon carbide. Sci. Rep. 6, 37077, (2016).

$$\frac{\delta B}{\sqrt{\Delta f}} = 400\frac{nT}{\sqrt{Hz}}$$

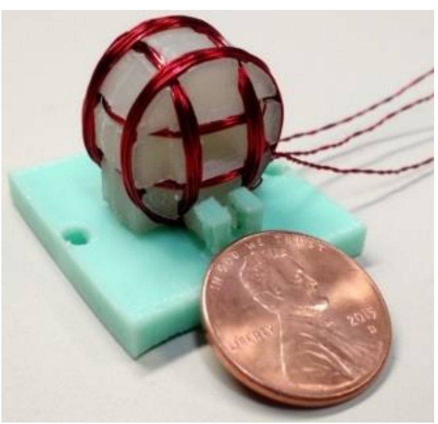
4H SiC MOSFET



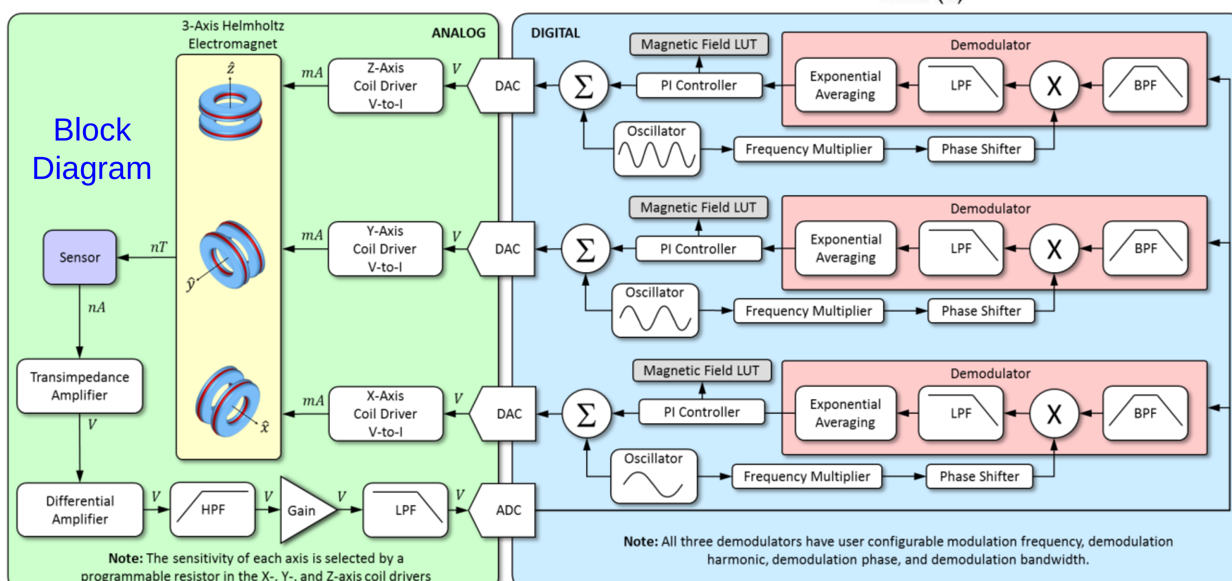
FDM Signal Processing



3-axis Helmholtz coil for magnetic field modulation and nulling



Block Diagram



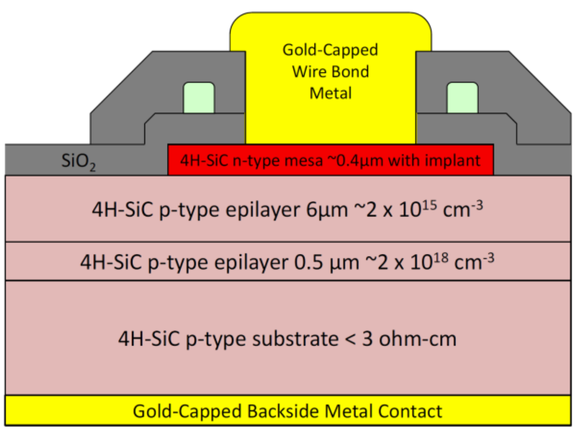
Nitrogen vs Phosphorous Implantation

- We evaluate the magnetic field sensing capability of two sets of nearly identical n+p diodes fabricated at NASA Glenn.

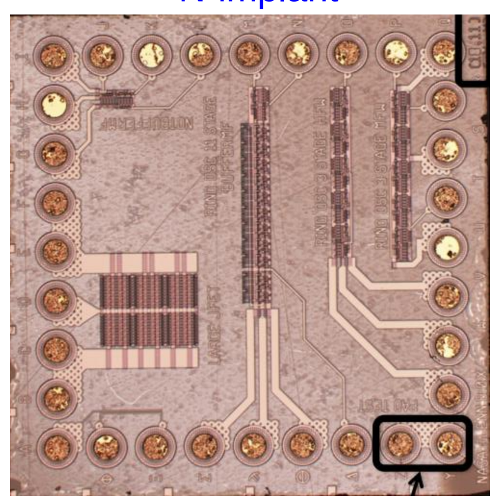
- The 250 µm diameter diodes were formed by the same high-dose n-type implantations used to make source/drain regions for two different JFET IC wafer runs, contacted by a 162 µm diameter IrIS metal stack [12-14].

- The major difference between the two sets of diodes is that one received a nitrogen (N) implant with a 4 hour activation annealing time while the other a phosphorus (P) implant with a ~100 hour activation annealing time

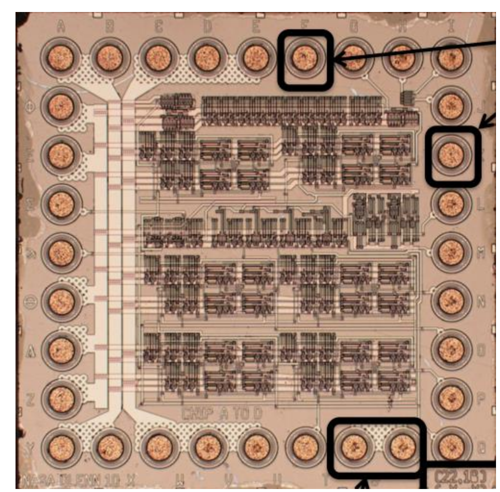
n-type N doped, p-type Al doped



N-implant

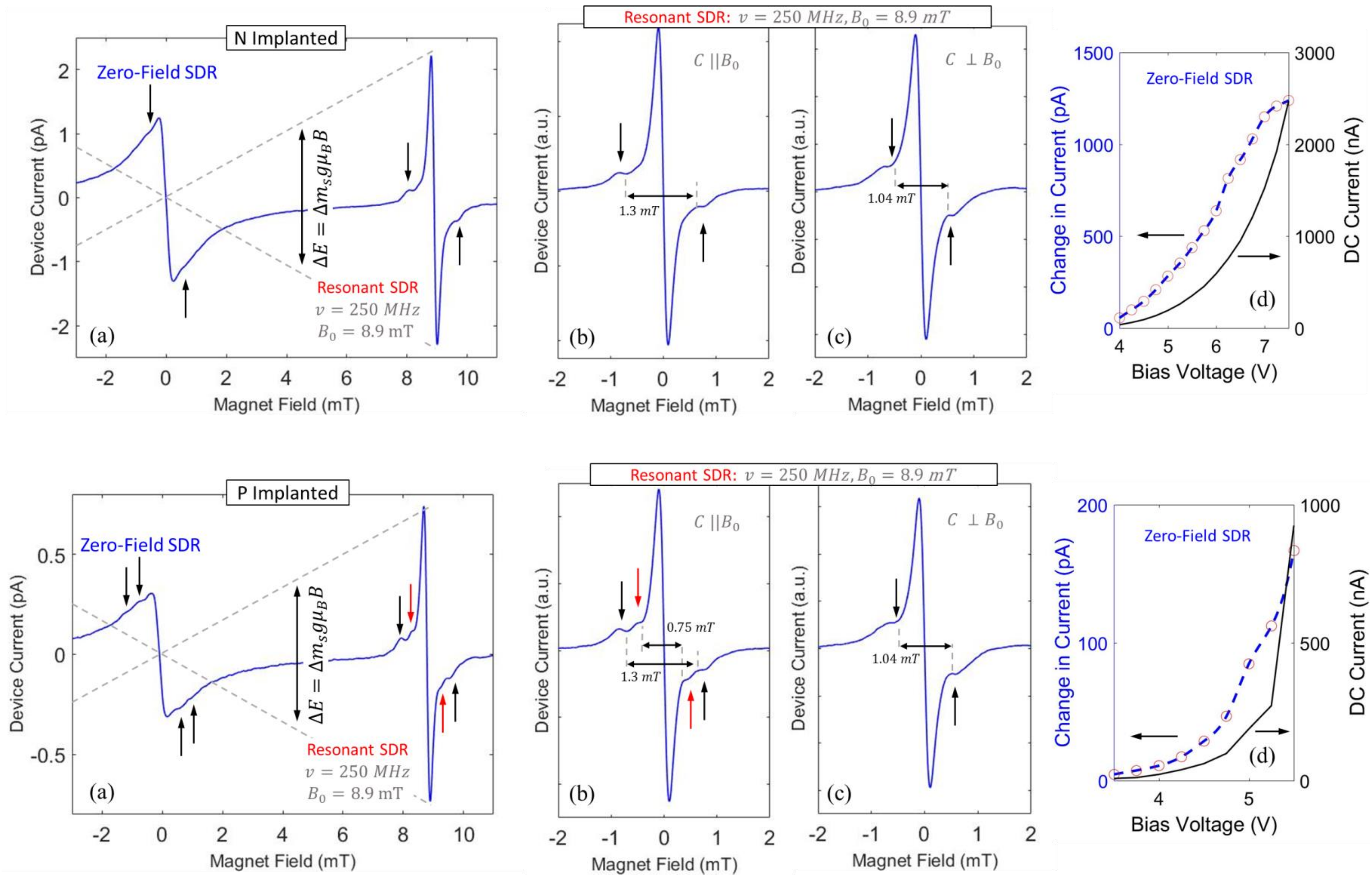


P-implant



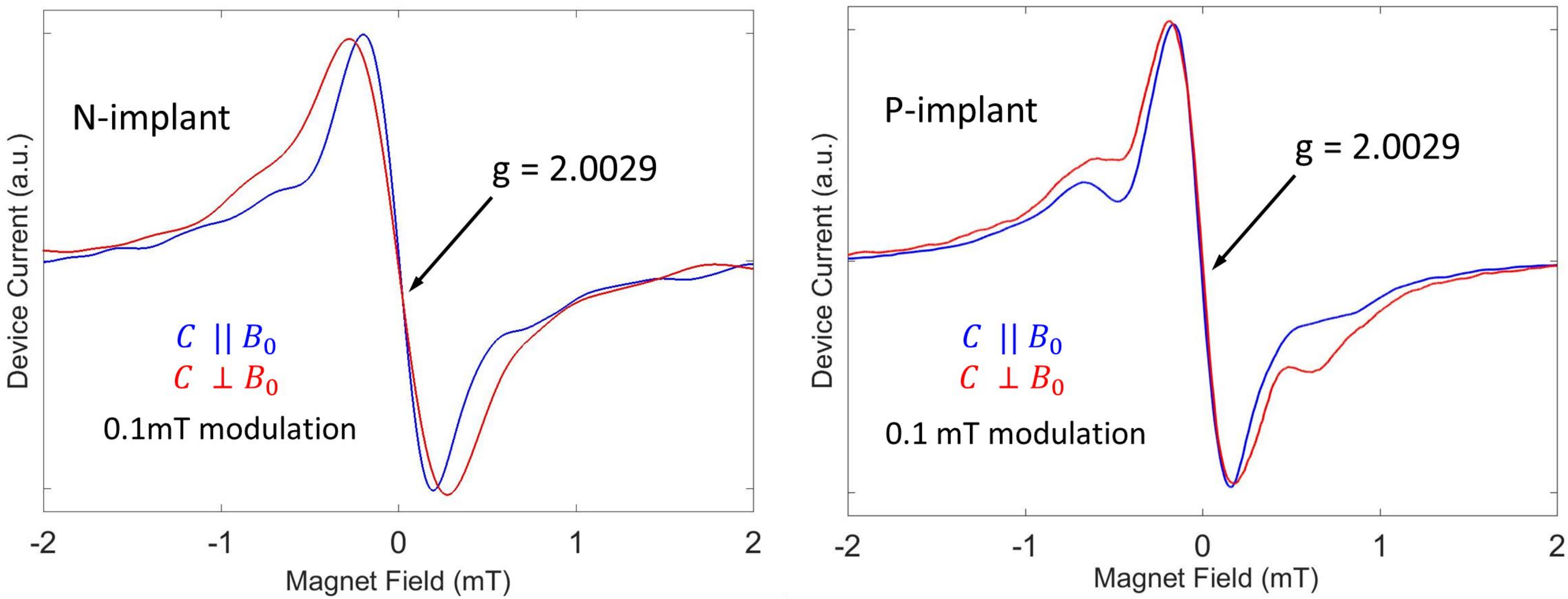
D. J. Spry, et al., *Mat. Sci. For*. 828 908-912 (2016), D. J. Spry, et al., *IEEE Elec. Dev. Lett.* 38 1082-1085 (2017)., D. J. Spry, D. Lukco, *J. Electron. Mater.* 41 915-920 (2012).

Low-Field EDMR Results



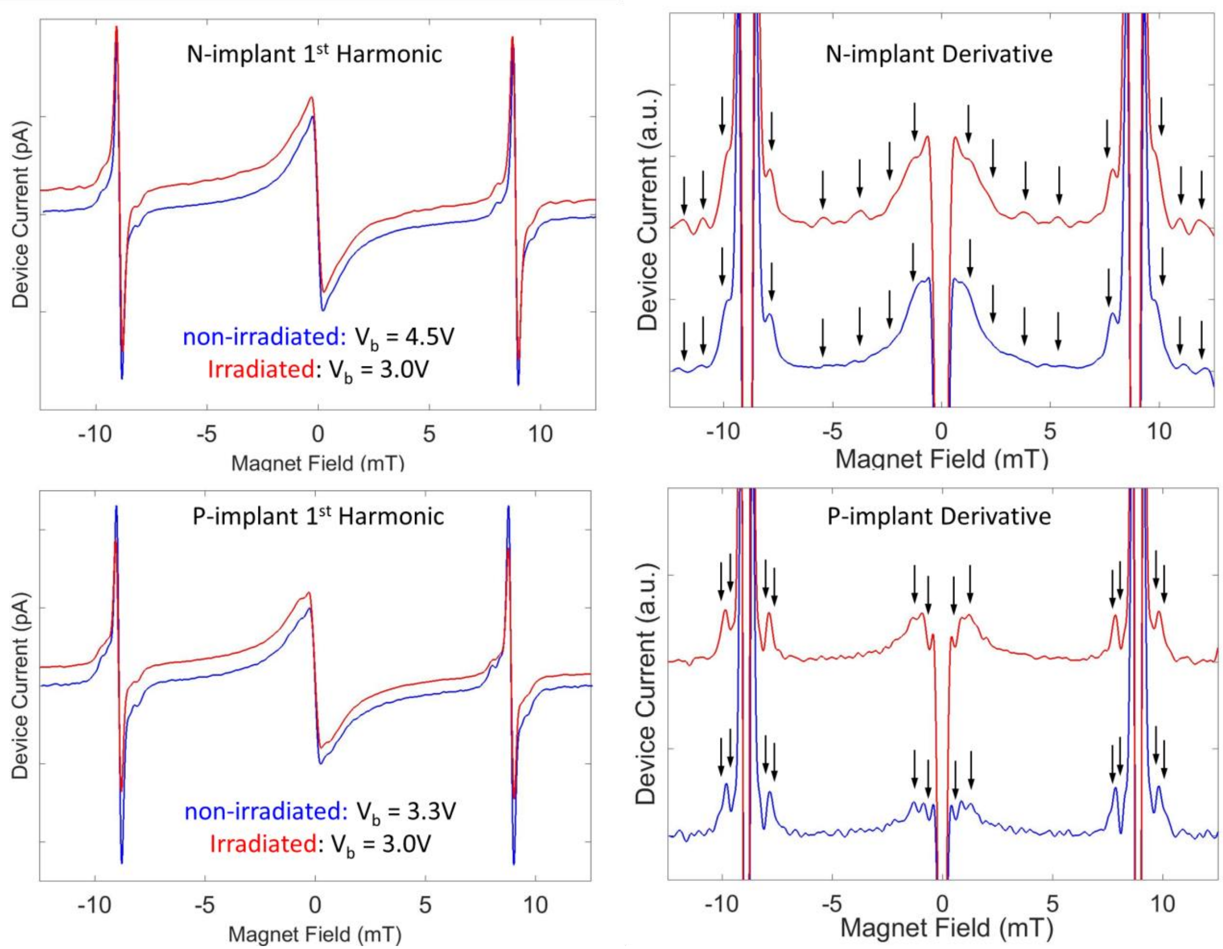
High-Field EDMR Results

- High field measurements made at Penn State University
- Indicate that the dominate defect likely a silicon vacancy, isotropic g ~ 2.0029 +/- 0.0003
- Hyperfine interactions are anisotropic and likely due to a different defect in large quantities as they appear to shift with respect to the center dominating line.



Effect of Radiation on Defect Spectrum

JPL's Dynamitron: electron irradiation, fluence of 1×10^{14} e^- / cm^2, E = 2 MeV, both contacts of the diodes tied to a common ground.

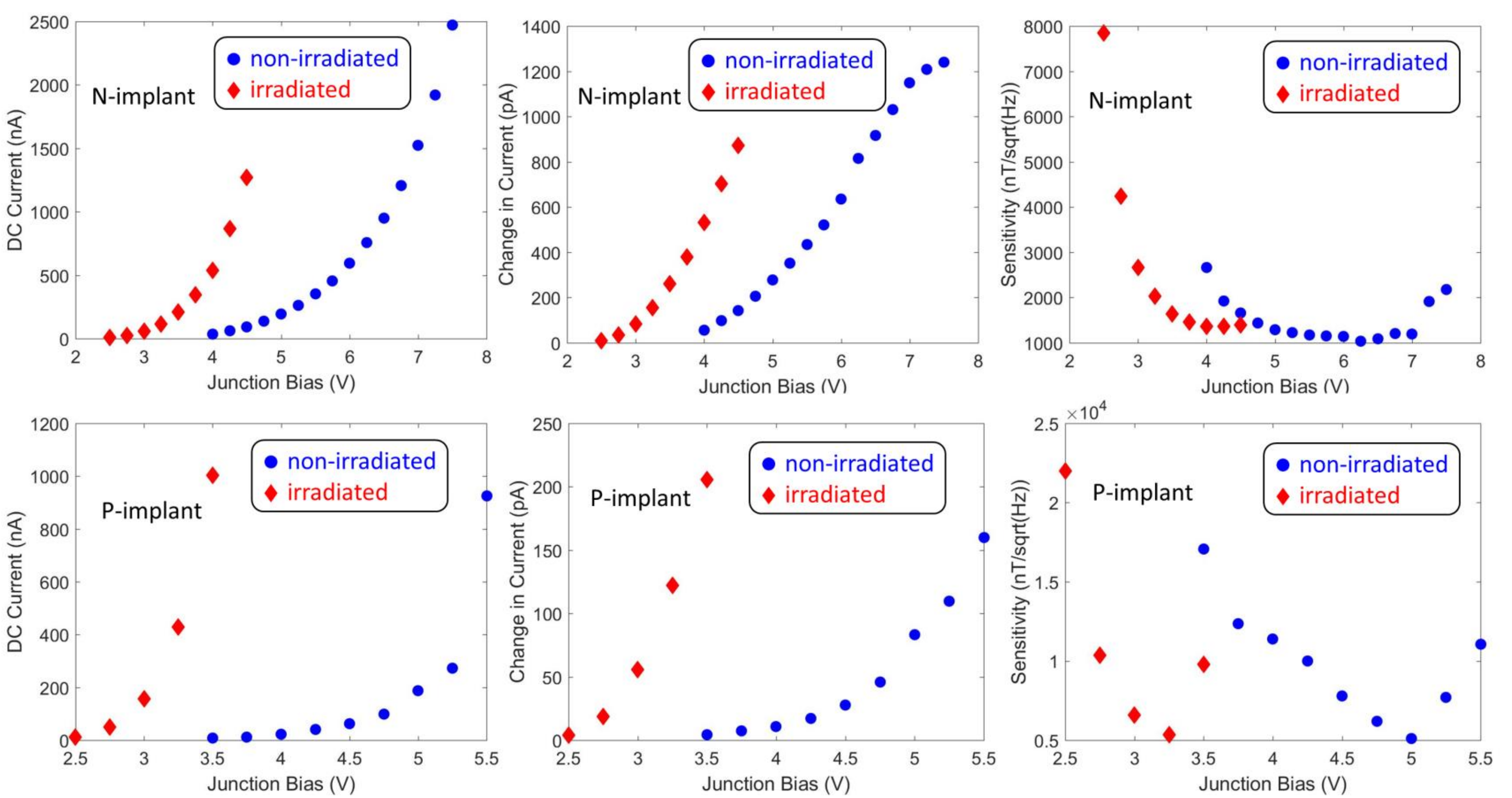


Effect of Electron Irradiation on Sensitivity

- Electrons effected the built-in voltage of the diodes
- Maximum sensitivity remains unaffected for both devices

$$\frac{\delta B}{\sqrt{\Delta f}} = 2\sigma\sqrt{\pi q}\frac{\sqrt{I_0}}{\Delta I}\left(\frac{T}{\sqrt{Hz}}\right)$$

DC current I_0
change in current ΔI
signal width σ



Applications and Future Work

- Applications
  - planetary entry probes
  - Landers
  - missions in extreme environments
  - swarms of spacecraft significantly smaller than current nanosats

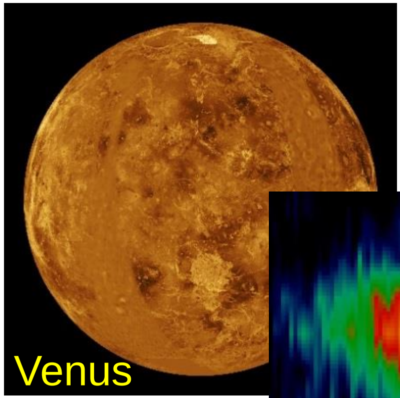
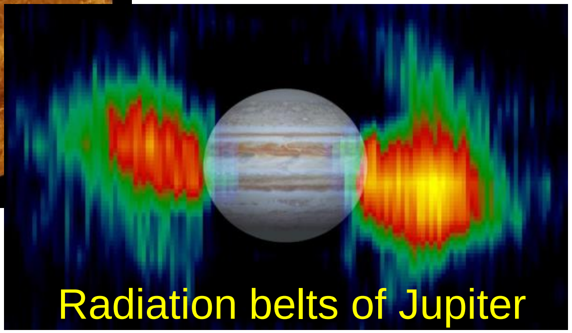
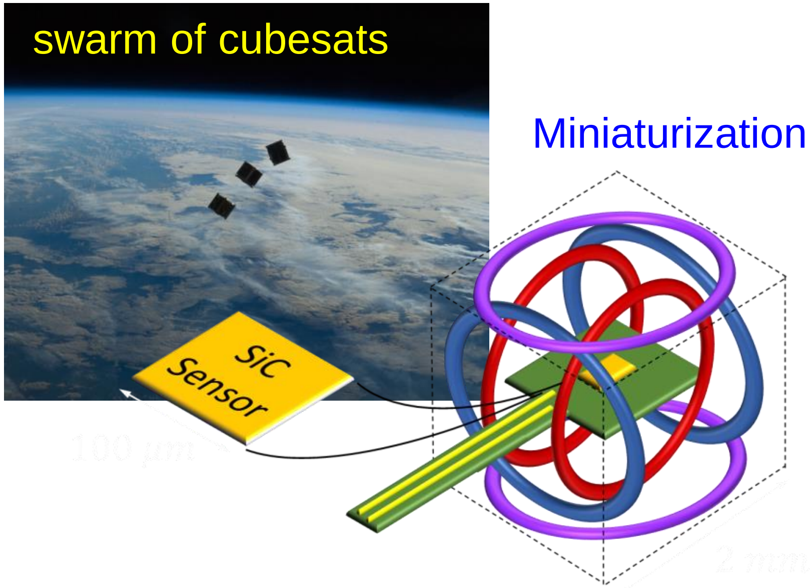


Image credit: NASA



- Future Work: Planetary Instrument Concepts for Advancement of Solar System Observations (PICASSO)
  - Model the observed response
  - Trade geometry, size, doping, and processing of sensor for optimal field detection
  - Fabricate customized sensor with NASA Glenn Research Center



Questions ???

Acknowledgement

The research described here was carried out at JPL, CalTech, under a contract with NASA, supported by PICASSO. Device fabrication at NASA Glenn Research Center was supported by both PICASSO and the NASA Aeronautics Transformative Technologies and Tools project.